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Development of a small-scale thermoelectric generator integrated with a waste oil stove

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Abstract

The growing accumulation of used motor oil, classified as hazardous waste (B3), presents an urgent environmental challenge. This research investigates the feasibility of generating small-scale electrical power using waste oil combustion in a stove integrated with a Thermoelectric Generator (TEG). An experimental setup was developed where the hot side of the TEG is heated by the combustion chamber of the stove and the cold side is cooled using a water block. Real-time temperature, voltage, and power output data were collected using an Arduino-based sensor system. The maximum observed temperature difference across the TEG module was 233 °C. Under open-circuit conditions, a peak voltage of 37.32 V was recorded, while the maximum output power under load reached 11.72 W at a current of 0.76 A. The system achieved its highest electrical efficiency of 0.182% at the peak temperature gradient. These results demonstrate the potential of TEG modules for converting heat from waste oil combustion into electricity, with optimal performance achieved under stable high-temperature gradients and consistent fuel supply.

Keywords:
Used oil stove, TEG, energy efficiency, waste heat conversion, energy independence

1 Introduction

The increasing number of vehicles will lead to an increase in the use of lubricants for vehicle engines and produce waste in the form of used oil. Used oil is classified as B3 (Hazardous and Toxic Material) waste, which can damage and pollute the surrounding environment if not managed properly [1][2]. The way to utilize used oil waste is as an alternative fuel for used oil stoves.

The research to be carried out is to convert the heat energy produced by the used oil stove into electrical energy is the main focus, namely by adding a thermoelectric generator module to the used oil stove. Thermoelectric generators can be used to recover waste energy to generate electricity using the principle of the Seebeck effect [3][4]. The working principle of the thermoelectric generator is to convert heat energy by utilizing the temperature difference on both sides of the thermoelectric module into electrical energy directly; the greater the temperature difference on both sides, the greater the voltage generated by the thermoelectric module [5]. The thermoelectric module has a cold side and a hot side; the hot side utilizes the heat on the wall of the used oil stove, while the cold side is given cooling using a water block. Cooling using a water block is more effective than air cooling [6]. Thermoelectric generator technology is environmentally friendly, efficient, durable, and capable of producing energy on a small and large scale, so it can be a solution as an alternative source of electrical energy, if further developed. [7].

The use of Thermoelectric Generator (TEG) is an approach that is environmentally friendly, efficient, and has the potential to generate electricity on a small or large scale. However, in the application of this technology, there are still gaps. First, the used oil stove in previous studies still relies on external energy sources such as PLN electricity to operate the blower, making it less ideal to be applied in areas that have not been reached by the electricity grid, as seen in the study of Zoel Akmal et al [8] and Widya Rahmadani et al [9]. Secondly, modifications of used oil stoves that are specifically tailored for integration with thermoelectric circuits have also not been done [10]. The stove design in previous studies has not accommodated an optimal flat contact surface for TEG installation and is not equipped with an adequate cooling system to maintain the maximum temperature difference.

Therefore, this research aims to address this gap by modifying the design of the used oil stove that can efficiently accommodate the TEG module, complete with a water-cooling system (water block) and customized layout. In addition, the electricity generated by the TEG is also designed to be utilized directly to support the blower system independently, thus creating a more integrated and applicable system, especially for remote areas.

2 Research methodology

2.1 Thermoelectric generator

TEG modules consist of pairs of N-type and P-type semiconductors connected electrically in a series configuration and thermally in a parallel configuration. In N-type semiconductors, electrons act as the main charge carriers. When the hot side of the module is heated, the electrons gain kinetic energy from the heat (thermal energy) and move towards the cold side (Fig. 1), and it's specification is shown in Table 1.

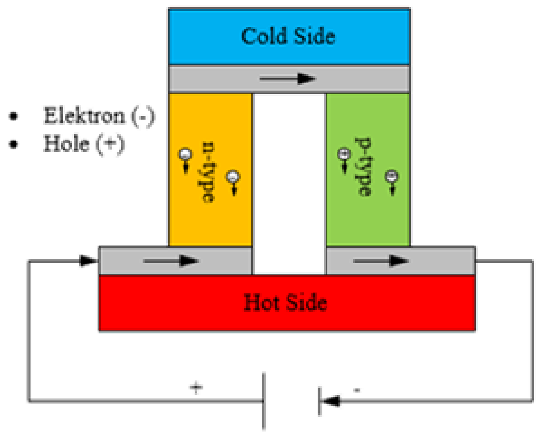

Fig. 1. Thermoelectric generator working principle [11]

Table 1. Thermoelectric generator specifications [12]

Parameter	Unit	Value
Dimention	mm	40x40x3.9
Temperature operation	C	0-150
Seebeck coefficient	V/K	0.054
Working Voltage delta 100c	V	6.4
Working Current delta 100c	A	0.969

Meanwhile, in P-type semiconductors, holes serve as the main charge carriers. This hole also moves towards the cold side, but electrically, its movement is equivalent to electrons moving in the opposite direction. The hot side of the module receives heat energy, while the cold side is kept at a lower temperature using a heatsink or other cooling system. This temperature difference (temperature gradient) creates an energy difference between the hot side and the cold side. In the process, electrons in N-type semiconductors move from the hot side to the cold side, while holes in P-type semiconductors also move towards the cold side. This movement of electrons and holes produces an electric potential difference between the hot side and the cold side, resulting in an electric voltage. When the module is connected to an external circuit, this potential difference allows the flow of electric current that can be utilized for various applications.

2.2 Basic theory

The efficiency of a thermoelectric generator can be described as the ratio of the electrical energy generated by the TEG (written as Pteg) to the thermal energy Qh entering the hot side surface of the thermoelectric generator. The temperature difference between the hot and cold sides of the TEG determines the amount of energy produced by the thermoelectric generator. Given the temperature-dependent nature of the TEG,

the calculation of the TEG efficiency is done first by determining the ZT. This can be done by applying direct current to the terminals of the thermoelectric circuit over a period of time and measuring the voltage at those terminals[13][14][15]. Due to the Peltier effect, the TEG module acts as a thermoelectric cooler and pumps heat from one side to the other. Due to the Seebeck effect, the change in temperature at the surface of the TEG generates an electrical current. The voltage generated by the current flowing between the terminals of the TEG circuit is called the Joule voltage, Vj. The Seebeck voltage, Vs, produced by the temperature difference due to the Seebeck effect, is called the Harman voltage. The difference between Vj and Vs is called the Harman voltage. Eq. (1) and Eq. (2) [16][17] It can be used to determine the merit amount.

$$ZT = \frac{\mathrm{Vs}}{\mathrm{Vj}} \tag{1}$$

TEG efficiency is calculated by Eq. (2) [15][3].

$$\eta TEG = \frac{\Delta T}{Th} \cdot \frac{\sqrt{1+\mathrm{ZT}-1}}{\sqrt{1+\mathrm{ZT}+\frac{Tc}{Th}}} \tag{2}$$

Where ΔT is the temperature difference between the hot and cold sides, Th is the hot side temperature, Tc is the cold side temperature, and ZT is the temperature-dependent ZT.

2.3 Harman method

Before conducting experimental work using the TEG, it was necessary to identify the ZT value of the SP1848-27145 SA TEG using the Harman method. The test is performed by connecting the thermoelectric generator to an external source with a constant direct current of 10 mA. Upon reaching a constant voltage output, the power was turned off (Fig. 2).

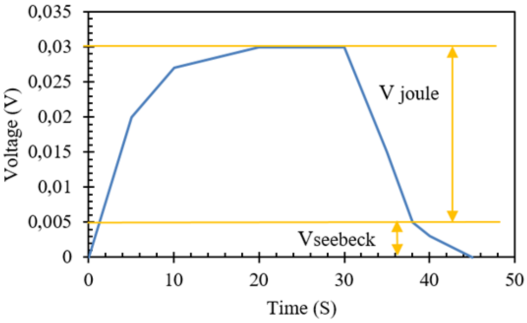

Fig. 2. TEG voltage profile obtained through the Harman method [15].

The voltage drop is monitored during thermoelectric generator operation. The voltage curve shows two voltage profiles: Joule voltage and Seebeck voltage. The Joule and Seebeck voltages are used to calculate the ZT using Eq. (1). The calculation results show that the ZT value of the thermoelectric module is 0.407.

2.4 Research procedures

The first step in this research is to recreate the used oil stove with a special design that can be installed in a thermoelectric module, where the thermoelectric module has a flat plane; for that, the stove design must have a flat cross-section on the furnace wall. The design of the used oil stove shown in Fig. 3 is the design of the used oil stove.

The next step is to make a tool based on the design that has been made, then assemble all the components of the used oil stove, such as the electrical system, thermoelectric system, installation of temperature data loggers, and electricity output data loggers shown in Fig. 4.

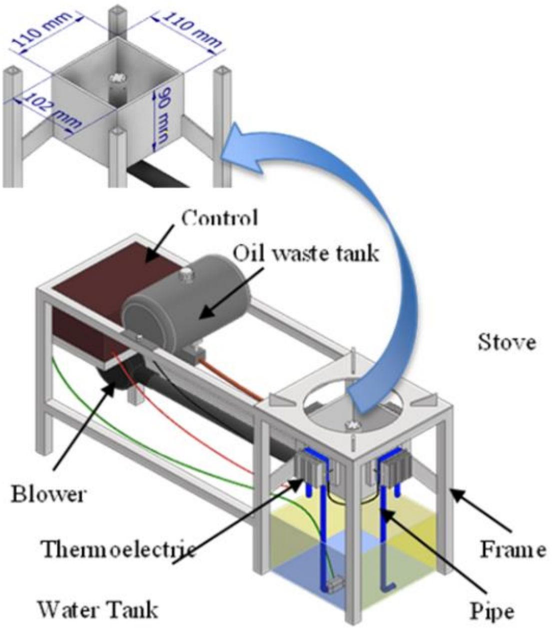

Fig. 3. Used Oil Stove Design

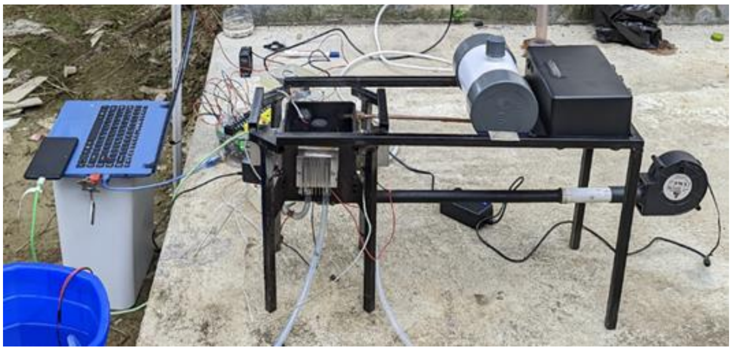

Fig. 4. Experiment Stove

Temperature data and electrical output is collected as shown in Fig. 5. The data collection process begins by turning on the used oil-fueled stove as the main heat source to include oil as fuel in the amount of 150 ml, this size is taken based on the capacity and height of the vent on the furnace cylinder. After the stove is lit stably, all supporting systems are activated, including the water pump, blower, and data logger for temperature and electrical output. Each of these components has an important role in ensuring that the testing process is optimized and the data obtained is accurate.

The water pump was set at a flow rate of 240 L/h, with a maximum voltage supply of 5 volts. The selection of a pump with a discharge capacity of 240 L/h is based on the technical specifications of the pump, which has a maximum voltage of 5 volts and is capable of producing a maximum discharge of 240 L/h. This capacity was chosen because it is in line with the maximum available pump limitations, ensuring optimal performance in the designed system. In addition, this study does not discuss the effect of different water discharges on the pump, so the selection of this capacity is considered adequate to meet the needs of the system without the need for further analysis related to variations in water discharge. This pump serves to circulate water through the pipe to the water block, which will be used to cool the cold side of the thermoelectric module TEG. With an efficient cooling system, the pump helps maintain the temperature difference required to maximize TEG performance.

Next, the blower was activated with an air velocity of 12.4 m/s. The selection of the blower speed with an air velocity of 12.4 m/s is based on the experimental results, which show that this speed produces a stable and blue flame, as shown in Figure 8, reflecting optimal combustion.

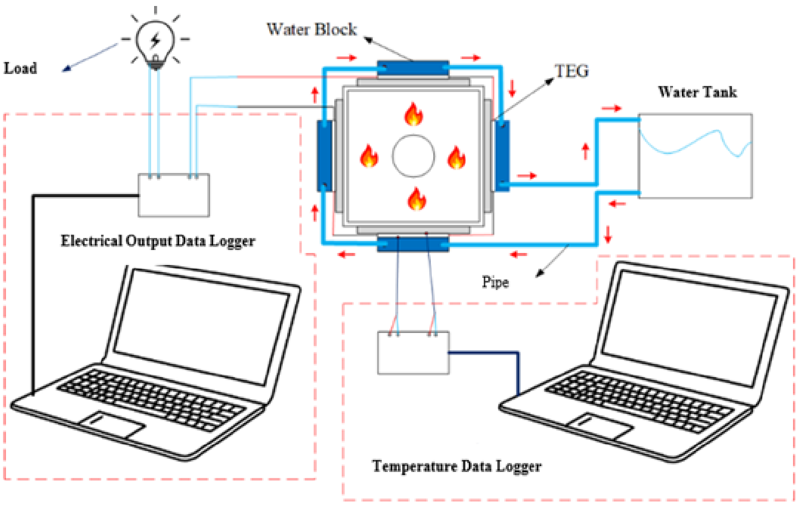

Fig. 5. Data capture scheme

At speeds below 12.4 m/s, the flames are not blue, are not constant, and tend to fluctuate until they eventually die out. Conversely, at speeds above 12.4 m/s, the flames tend to extinguish easily and expand excessively in the upward direction, which is not recommended in this study. In addition, this study does not discuss the effect of different air velocities on the blower, so the selection of 12.4 m/s is considered the most ideal condition for the needs of the designed system. This blower has an important role in maintaining the stability of the flame on the used oil stove. With consistent airflow, combustion can take place more stably and optimally, so that the heat generated is maintained in ideal conditions for testing.

On the temperature data monitoring side, an Arduino Uno-based MAX6675 sensor is used, which is connected to a type K thermocouple. This sensor is placed to monitor the temperature of the hot side and cold side of the TEG. The temperature data obtained is then sent to a PC or laptop to be observed directly. This system allows researchers to monitor the temperature difference that occurs in real-time during the testing process.

In addition, the electrical output data from the TEG was also monitored using an Arduino Uno-based INA226 sensor. Four thermoelectric modules were assembled in series, with the positive and negative terminals connected directly to the electrical output data logger. To confirm the presence of load on the system, a DC LED lamp was installed and connected to the data logger circuit. The voltage and current data generated by the TEG can then be observed directly through a PC or laptop connected to the data logger.

During the data capture process, the hot and cold side temperatures of the TEG, as well as the electrical output of the thermoelectric circuit, are continuously monitored and recorded. The Arduino-based monitoring system connected to the PC or laptop enables accurate and real-time data recording, providing the necessary information for further analysis of the efficiency and performance of the thermoelectric system under test.

3 Results and discussion

3.1 Voltage and current electrical output profile

Fig. 6 shows the relationship between temperature difference (ΔT) with voltage (in blue) and electric current (in red) in the Thermoelectric Generator system. At low ΔT (0-56.25°C), both voltage and current are still very low because the Seebeck effect is not yet significantly active. Entering ΔT 56.25-124.75 °C, the voltage starts to rise sharply to about 12.13 V, indicating an increase in the conversion of heat energy into electricity. The current also starts to rise significantly, reflecting the increased power generated by the system. At ΔT 124.75-198.25 °C, the voltage increases more slowly and approaches saturation at around 12.13-14.44 V, while the current continues to increase until it approaches 0.8 A. After ΔT exceeds 198.25 °C, the voltage and current both tend to stabilize or steady state, indicating that the system has reached the maximum limit of its energy conversion. Minor fluctuations in both current and voltage data may come from resistance variations, temperature irregularities, or load characteristics, as well as the reduction of used oil fuel in the stove (Fig. 7).

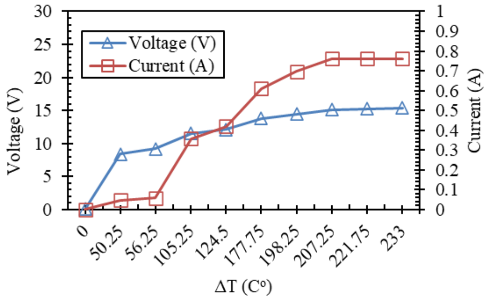

Fig. 6. Profile of voltage and current versus temperature difference

(a)

(b)

Fig. 7. Used Oil Stove Testing (a) daytime, and (b) Nighttime

Overall, the system works most efficiently up to a ΔT of around 180-200°C, after which an increase in temperature no longer results in significant electrical output

3.2 Electrical power output profile

Fig. 8 shows the relationship between the electrical power generated by TEG and the temperature difference (ΔT) between the hot side and the cold side. At low ΔT (0-56.25 °C), the power generated is almost zero because the temperature gradient is not yet sufficient to generate a significant thermoelectric voltage. The power increase starts to occur sharply when ΔT exceeds 100 °C, indicating that the TEG material starts to work in the optimal efficiency zone, with the power continuing to increase almost linearly until it reaches about 12 W at ΔT around 198 °C. Thereafter, the graph shows a saturation trend, where increasing ΔT up to 233 °C no longer results in a significant increase in power. .

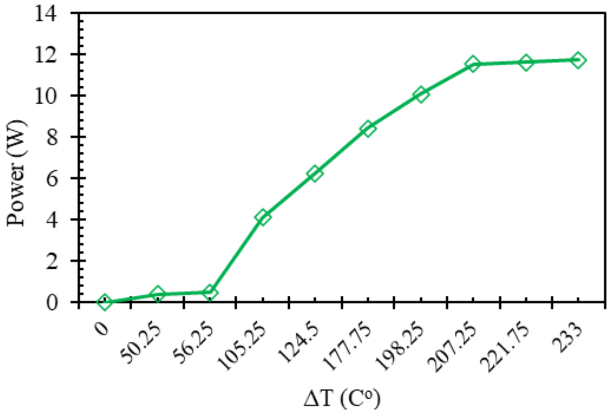

Fig. 8. Electrical power output

This pattern reflects the general characteristics of TEGs, where the conversion of heat energy to electricity is most efficient in the ΔT range of 100-200 °C, while beyond that range, the efficiency decreases due to limitations in material properties and increased internal resistance as well as reduced oil fuel

3.3 Output voltage open (VOC)

Fig. 9 shows the relationship between the VOC of the TEG against the ΔT between the hot side and cold side of the TEG module. It can be seen that the VOC increases as ΔT increases, reflecting that an increase in the temperature gradient provides a greater thermal electromotive force boost through the Seebeck effect. Initially, the voltage increase is quite significant between ΔT 0 to about 124.5 °C, indicating optimal thermal to electrical conversion efficiency within this range. However, after ΔT passes 198.25 °C, the graph shows a saturation trend, where the voltage increase starts to slow down and even flatten out, indicating that the semiconductor material in the TEG starts to reach the limit of its conversion capability, or thermal-electrical performance degradation occurs. This phenomenon is important to consider in the design of thermal energy harvesting systems, as it shows that the maximum efficiency is not always linear to the increase in temperature, and there is an optimal point ΔT to generate electrical power efficiently.

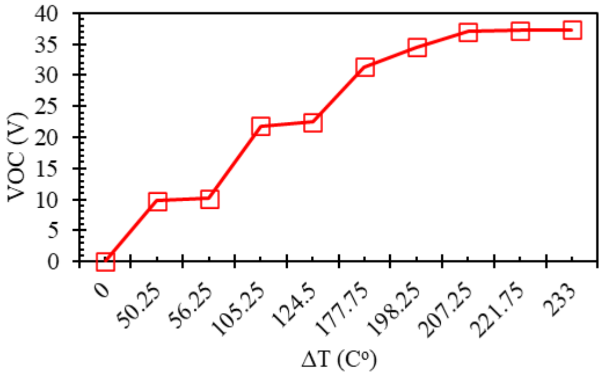

Fig. 9. Open electrical output VOC

3.4 Efficiency

Fig. 10 shows the relationship between electrical efficiency (%) and temperature difference (ΔT) of the Thermoelectric Generator (TEG). It can be seen that the efficiency increases as ΔT increases, which indicates that the TEG works more optimally when there is a larger temperature difference between the hot and cold sides. At ΔT near 0°C, the efficiency is almost zero, but starts to increase significantly at ΔT around 50°C until it reaches about 0.18% at ΔT around 233°C. This pattern of efficiency increase tends to plateau after ΔT around 198°C, indicating a point were increasing the temperature no longer provides a comparable rise in efficiency.

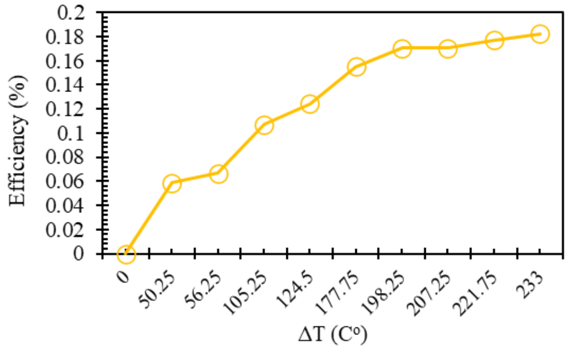

Fig. 10. Efficiency

This reflects the characteristics of thermoelectric materials, which have optimal efficiency limits, as well as the possibility of increased thermal resistance or saturation effects. Overall, this graph confirms the importance of maintaining a high temperature difference between the sides of the TEG to maximize the efficiency of converting heat energy into electricity, but also shows that there is a practical limit to the efficiency improvement, even if ΔT is increased

4 Conclusion

The TEG-based system has converted thermal energy from waste oil combustion into electrical energy. Its performance significantly influenced by the temperature difference (ΔT) between the hot side and the cold side.

The experimental results are concluded as the following: Firstly, Voltage and current output began rising significantly at ΔT ≈ 56 °C, reaching optimal power generation performance in the ΔT range of 180–200 °C. Secondly, Maximum power output of 11.72 W and current of 0.76 A were recorded at ΔT ≈ 198 °C, with open-circuit voltage peaking at 37.32 V. Thirdly, Electrical efficiency increased with ΔT, reaching a maximum of 0.182% at ΔT = 233 °C, though further efficiency gains plateaued due to material and system limitations.

These findings highlight the need for optimized thermal management to maintain the temperature differences within the 180–200 °C range, ensuring sustained power output and improved system performance. The integration of TEG modules with waste oil stoves offers a low-cost solution for decentralized electricity generation.

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